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Perspectives on industrialized transportable solar powered zero energy buildings

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ABSTRACT

Decreasing prices of photovoltaics (PV) and Lithium-ion batteries are creating a significant momentum for off-grid Zero Energy Buildings (ZEBs). In literature, most researchers have focused on grid-connected ZEBs built on site. This literature review is written with factory-made off-grid ZEBs in mind. High investment costs, poor construction quality and problems to achieve ZEB in real operation are three challenges that ZEB buildings currently face. This article discusses how automated mass production of continually improved standardized modules can overcome those problems. A shipping container is chosen as the modular unit to take advantage of the existing transport infrastructure. Due to the narrow width, the potential for utilizing daylight is better than that of traditional buildings. Off-grid ZEBs mean that the user must achieve ZEB in real operation, including plug loads. The local energy generation is likely to motivate the users to learn more about renewable energy. Plug loads is the largest energy consumer in buildings but are still often overlooked in ZEB definitions. With the Belt and Road initiative and political incentives to increase industrialized construction in China, the premises for exporting container buildings to the main markets in Asia and Africa are improving.

1. Introduction

The economic growth and an additional 1.7 billion people by 2040 will fuel an increase in emissions, based on the historical relationship between economic growth and emissions. Electricity consumption in large areas like Russia, India and the Middle East is expected to rise 10–15% per point increase in GDP as the economy grows. The global emissions will slightly increase by 2040, based on announced policies and targets [1]. How shall the Intergovernmental Panel on Climate Change's (IPCC) recommended 77% reduction in CO_2 emissions be met [2]?

Globally, there will be a 30% rise in energy demand in buildings by 2040, according to IEAs main scenario [3]. Buildings are expected to remain the largest consumer of electricity and the largest cause of growth. The electricity demand in buildings is expected to grow by 60% on average by 2040. The growth is mainly caused by developing countries, who will have a 90% growth in the electricity demand by 2040. Energy efficient buildings are therefore required for a sustainable development strategy. Zero Energy Buildings (ZEBs) have therefore become a common solution, but high construction costs have been considered an obstacle for ZEBs, together with lack of knowledge among the constructors. Our hypothesis is that industrial constructions can solve this problem by producing standardized, modular ZEBs factories-made from shipping containers.

Energy saving measures should be carried out to the point where the marginal costs of energy generation are lower than the costs of energy saving measures. The second question is how enough renewable energy shall be provided? The power sector is responsible for more than 40% of the world's primary energy demand in 2017 and for more than 40% of energy-related CO_2 emissions [4]. The fact that there has not been any

Abbreviations: +NZEB, Plus Energy Building; BIM, Building Information Modelling; BIPV, Building Integrated Photovoltaics; CERC, China Clean Energy Research Center; CHP, Combined Heat and Power; COP, Coefficient of Performance; DREA, Distributed Renewable Energy Access; EAHP, Exhaust Air Heat Pump; EBC, Energy in Buildings and Communities Program; EPBD, Energy Performance of Buildings Directive; ETC, Evacuated-tube collector; HESS, Hybrid Energy Storage System; IEA, International Energy Agency; IPCC, Intergovernmental Panel on Climate Change; LBNL, Lawrence Berkeley National Laboratory; LCA, Life Cycle Analysis; LCC, Life Cycle Cost; LCOE, Levelized Cost Of Electricity; MOO, Multi-Objective Optimizations; MPC, Model Predictive Control; MPC, Model Predictive Controls; nZEB, Nearly Zero Energy Building; NZEB, Nearly Net Zero Energy Building; NZEB, Net Zero Energy Building; PAYG, Pay As You Go; PCM, Phase Change Material; PMV, Predicted Mean Vote; PPD, Predicted Percentage of Dissatisfied; PSO, Particle Swarm Optimization; PV, Photovoltaics; PV/T, Photovoltaic/Thermal; SHGC, Solar Heat Gain Coefficient'; VIP, Vacuum Insulation Panels; ZEBs, Zero Energy Buildings

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growth in the share of renewables in the power sector over the last ten years, shows that there are still problems with integrating enough renewable energy in the power grid at a competitive price [4]. The total share of fossil fuels in the world's primary energy demand is still the same as it was 25 years ago [1]. What is estimated to be the most economical way of generating electricity to keep the increase of the global average temperature well below 2 °C?

According to IEA's latest Sustainable Development scenario, the global Photovoltaic (PV) capacity should rise to more than 4200 GW by 2040 with nearly 60% of new installations being mini-grid or off-grid solutions by 2030 [1]. Around two thirds of the mini-grids and three quarters of the off-grids should be PV-powered. Developing countries like China and India, who will together contribute to 48% of the increase in the global primary energy demand between 2017 and 2040, have adequate solar conditions and faster expanding PV than any other countries.

This article discusses whether industrialized transportable off-grid Zero Energy buildings could be a reasonable approach considering the market needs and the recent technical development. Based on literature review of this field, most researchers have focused on grid-connected Zero Energy Buildings that are built on site. The targeted audiences are researchers and designers who are new to the field. This article gives an overview of how to plan such buildings and provides a framework for further studies. The sections about the state-of-the-art for ZEB, PV and industrial construction can also be interesting for investors and decision makers.

The article starts by looking at ZEB buildings in general, by presenting different definitions of ZEB, the ZEB development around the world and the related challenges. Important design aspects for residential ZEBs are presented in chapter 2, with the main focus on heating, cooling, ventilation and renewable energy supply. Although chapter 2 is relevant for ZEBs in general, the main emphasis is on solutions that are relevant for the transportable, solar powered ZEBs that are presented in chapter 4. After the benefits of industrialized construction are presented in chapter 3, the shipping container will be described to be the most adequate modular unit. Different design solutions for container buildings are presented in chapter 4 before the current challenges and future research opportunities are discussed in chapter 5.

2. State-of-the art for ZEB

2.1. Definitions of ZEB

Several different ZEB definitions exist, which makes it necessary to clarify how the term is to be interpreted in this article. Zero Energy Buildings can be either off-grid or grid-connected. Fig. 1 gives an overview of some common ZEB definitions. For an extended list of definitions, see Table 1 in D'Agostino and Mazzarella [5]. A NZEB (Net ZEB) is a building that use 0 kWh/(m^2 a) primary energy [6]. Nearly Net Zero Energy Buildings (nNZEB) has been the main focus in the EU, where the required amount of primary energy that shall be covered by renewable energy is to be decided on national level based on what is reasonable technically and economically [6]. Usually the total primary energy need of a nNZEB should be around 50 kWh/m^2/year [1]. The research in Europe has focused on definitions, boundaries, types of energy use to be included, calculation methods, metrics and period of balance [7]. Distinctions between energy and primary energy and between energy carriers and energy sources are also frequently debated [5]. D'Agostino and Mazzarella [8] provides data on energy consumption in residential buildings in the EU member states. It is concluded that most nNZEBs in Europe are still demonstration projects. nNZEB have gained more attention over the recent years, but are still not uniformly implemented [5].

The energy need for buildings in the EU mainly stems from space heating (70%) [5]. Residential buildings represent around 75% of the building stock in terms of floor area [9]. Building renovations are important because the majority (75%) of buildings existing today will still be there by 2050 [10]. The long lifetime of buildings also imply that it is urgent to provide cost-competitive ZEBs as the new buildings will impact future energy demand for roughly 50 years.

A Plus Energy Building (+NZEB) have an excess of renewable energy generation and could therefore have a net export of primary energy over the year [7]. Research on smart Energy Flexible Buildings are following the research on ZEBs in the EU in order to increase the utilization of renewable energy and keep the grid stable [11]

USA Department of Energy defines four kinds of NZEBs: site NZEB, source NZEB, emissions NZEB and cost NZEB [12]. The definition involves different elements, such as: limits, weighting factors, metrics and conditions [13]. A site NZEB is defined as a building that, at its site, generates at least as much net energy than it consumes. For a source NZEB, the difference is that the metric is primary energy and not net energy need. An Emissions NZEB refers to a building that generates enough renewable energy to cover up for all the emissions from its net energy needs, while a cost NZEB means that the building owner has net zero energy costs. Most European and US ZEB definitions choose a balancing period of one year to determine the net energy need [14].

It is obvious that the fulfillment of the site NZEB definition itself does not guarantee that the building is designed in an energy efficient way [15]. Calculations of the CO_2 balance and primary energy need will further specify the environmental impact of the building compared with other design solutions. A Zero Emission Building is a step towards a Life Cycle Analysis (LCA), which should be the final aim. LCA considers the lifetime environmental impacts of material manufacturing, construction, use, maintenance and waste disposal at the end of life. The goal is to limit the use of resources to an ecologically sustainable level. The operational impacts in a typical building account for 80–90%, but this percentage is lowered as the operational efficiency improves [16]. Particularly, it is interesting to see which elements make the largest contribution to the total impact, to understand opportunities for improvements. The life-cycle CO_2 emission is estimated at each stage according to consumed energy and resources. Two international standards, ISO 14040 and ISO 14044, provide the framework for completing an LCA. A LCA typically aims to account for 99% of both the mass of a product and the energy used in its production [17]. A flow chart can be used to visualize resources, emissions, product flows and waste flows. Two of the greatest challenges are to acquire data and make judgements about where to set the system boundary and which assumptions to make. BIM models makes it easier to access data about quantities of building materials used. Autodesk Revit now has LCA plugins like One Click LCA. LCA can also be used on the component level to compare two alternatives, for instance a window produced

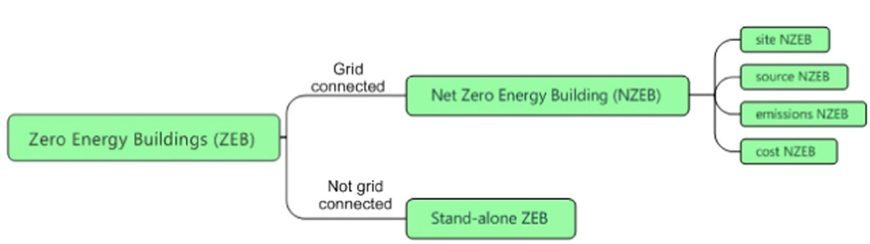

Fig. 1. Zero Energy Building definitions.

Table 1
Major performance of the kind batteries [80,82–84].

	Investment cost [¥/kWh]	Energy density [Wh/kg]	Energy density [Wh/L]	Lifetime expectation [cycles]	Charging time [h]	Requires maintenance
Li-Ion	2500	150	250	2000–4000	2–3	No
Lead acid	700	40	80	400–1500	12–16	Yes

locally against an imported one. The LCA for a window can be set up in a "nutrition label" style and list LCA impact measures like primary energy consumption and global warming potential. Currently, the differences in labor costs mean that products are transported around the globe to be manufactured and assembled [18]. LCA will favor reused, recycled and locally sourced materials [16]

Due to multiple ZEB definitions and various requirements for ZEBs in different countries, it is easy to understand that misunderstandings are frequent. A clearer international definition with specific criteria would provide a framework for countries to develop clear policies to support ZEBs [19]. The definition should encourage the building standard to improve within realistic economical constraints, without making the analysis too complicated.

In the EU, the Energy Performance of Buildings Directive (EPBD) gives the member states much freedom to customize the NZEB definition, making it hard to establish common benchmarks [5]. Due to the heterogeneity in buildings, labor costs, material prices, energy costs and climates in the member states, the energy performance level "which leads to the lowest cost during the estimated economic lifecycle" needs to be chosen. In 2016 it was shown that a significant share of national nZEB definitions did not meet the intention in EPBD, which is to achieving very low energy need and mainly use renewable energy [20]. The national cost-optimal minimum requirements must be reviewed every fifth year and the latest reports are from 2018 [21]. Commonly included in the nNZEB definitions are requirements for space heating and cooling, hot water and ventilation. Auxiliary energy, lighting and appliances are included in some countries' ZEB definitions, but left out in others. It is most common to consider single buildings with on-site energy generation.

2.2. ZEB development in Europe, USA and China

In Europe, the Energy Performance of Buildings (EPBD) claims that all new buildings must be nearly ZEB by the end of 2020. France aims even higher and asks that all new buildings should comply with energy positive goals by 2020 [13].

Three quarter of the buildings in the EU are inefficient, creating an economic incentive to reduce energy needs and CO_2 emissions by around 5% each [21]. Energy saving measures would also generate more jobs, but after the financial crisis of 2007 there have been less funding available [22]. The 2010 Energy Performance of Buildings Directive (EPBD) and the 2012 Energy Efficiency Directive are the legislative means through which the EU improves energy efficiency in buildings. EPBD has been implemented through national building codes that have set stricter requirements for energy efficiency in buildings. The EU has committed itself to the energy efficiency target of reducing energy consumption by 20% by 2020. By March 10th, 2020, all member countries shall have transposed the revised EPBD from 2018 into national laws. The target is a 32.5% reduction by 2030 [23]. Automated control system, for instance for control of temperature at room level, are among the new requirements. After December 31st, 2018 all new public buildings shall be nearly-zero energy buildings. The EU Building Stock Observatory has a database that monitors building energy performance in the member states [24]. Together with requirements for energy certificates in all buildings that shall be sold or rented, it keeps an awareness about energy efficiency. In 2018 the Smart Finance for Smart Buildings initiative was approved, seeking to boost private investments in energy efficiency in residential buildings with EU grants as a guarantee [25]. Such incentives are needed, as the energy consumption in EU has increased for three consecutive years [23]. A study of 12 pilot nZEB projects showed that the initial cost on average was 11% higher than conventional buildings [26]. A survey showed that a higher construction cost was the main barrier for green buildings among buildings professionals [27]. Although the investment pays off, they feel the payback time is too long. Financial support that helps to share the risk and overcome the high initial cost has proven to be successful in increasing investments in PV [28]. Hopefully, these grants will promote the sales and competition amongst vendors and permanently lower the prices of energy saving measures.

Denmark is one of the countries who has succeeded to achieve a high share of energy-efficient buildings. Since the 1970s, Denmark's financial incentive have been elevated energy and carbon taxes. Standards, taxes, subsidies and energy labelling motivated the Danish society to adopt ZEB goals [14].

Generally, the Northern countries in Europe have adapted better to the nZEB standard, as the building standard is already going towards a passive house standard [29]. It might be challenging to produce enough renewable energy only from solar PV, but using biomass in small-scale combined heat and power (CHP) can be a viable option in Scandinavia, where there is much wood available [30].

Attia, et al. [29] studied the barriers for nZEB in Southern Europe. Several of the countries were still to approve the nZEB legislation and were developing national plans. Both heating and cooling systems are usually needed in those locations, which increases the cost. Many European countries set a requirement stating that the zero energy buildings shall have a yearly heating and cooling need below 15 kWh/m^2, according to the passive house standard. But this is difficult to achieve in warm climates. Overheating has often been a problem for passive houses in those countries. On the other hand, the sunny climate means that solar thermal can reduce energy costs for space heating and heating of hot tap water [31]. Another challenge in Southern Europe is that highly efficient windows designed for cold climates may not be adapted to window shading.

USA also aims to set ZEB as their new standard between 2020 and 2025 [32,33]. In the US, the number of ZEB projects increased by over 700% the last six years. At least 135 local governments in North America have implemented roadmaps to ZEB. That is more than twice as many as 18 months ago [34]. Even in the coldest climate zones, ZEB have been achieved by focusing on airtight, insulated envelopes, passive design, and operation management. The five states with most ZEB's in the US all have ZEB policies that drive the investments. The success of these policies can be seen by a 33% increase in residential ZEB's in 2016 and an 82% increase in ZEB projects [34].

China currently has the world's largest primary energy consumption (23%) [35] and is accounting for 50% of new construction globally [36]. Buildings were responsible for over 30% of total Chinese energy consumption in 2010. This number is expected to increase to nearly 40% by 2020, the same level as the world's average. [37,38]. Energy efficiency in Chinese buildings is consequently essential in order to reduce emissions. China should reduce their emission by 60–65% by 2030 according to the Paris Agreement. They explicitly mentioned efficiency gains in electricity generation and in buildings as two of their contributions to the 2015 climate summit [39]. China's five year plan from 2016 to 2020 includes a requirement that 50% of all new urban buildings shall be certified as green buildings [40]. Green buildings do not only include energy-efficiency requirements but also water and

material efficiency, indoor environment enhancement, and waste reduction goals [14]. ZEB buildings are also attractive to the Chinese government because they meet their electrification policies which seeks to replace decentralized coal and oil burning. Today, Chinese homes emit about 470 Mt CO_2 from direct combustion, mainly from coal [1]. This number triples if the emissions from electricity consumption is included. This year, China set a target to distribute solar PV. The building sector contributes to 40% of the growth of China's electricity demand projected for 2040, with around 15% growth in home appliances, 15% for space cooling and 10% for space and water heating [1]. The total electricity demand in China for both household appliances and cooling more than doubles.

2.3. International ZEB research projects

The Energy in Buildings and Communities Program (EBC) from the International Energy Agency (IEA) has coordinated various research projects associated with energy predictions and energy efficiency measures. They aim for near-zero primary energy use and near-zero CO_2 emissions from new buildings by 2030 [41]. EBC may consequently be a driving force for the development of an international ZEB definition.

Building Energy Efficiency is also one of five focus areas in U.S. – China Clean Energy Research Center (CERC). The current research period from 2016 to 2020 is supported by public and private funding of at least $250 million total [42]. Among the focus areas within Building Energy Efficiency are industrialized buildings, developing an open source framework and software that will enable occupancy responsive model predictive controls (MPC) for various indoor spaces, techno-economic analysis of DC power distribution systems and development and demonstration of advanced air cleaning materials [43].

2.4. Common solutions

To describe the trends in the research of ZEBs, some common solutions are listed below. Based on the opinion of 179 building professionals from 8 European countries, energy efficient windows seem to be a frequent passive solution. For active solutions, the extensive application of heat pumps and heat recovery units in ventilation is noteworthy [20]. Most of the energy consumption in buildings is related to the use of active systems to maintain the comfort level [44].

Among the existing renewable energy technologies, solar thermal and PV systems are undoubtedly the most popular [20].

Envelopes with Vacuum Insulation Panels (VIP) and thermal break elements, triple pane glazing in high quality frames with vacuum insulation, high air tightness, utilization of the sky for passive cooling, cooling ceiling with a combination of water and paraffin-wax Phase Change Material (PCM) are other recommended elements to consider [45].

2.5. Challenges for ZEB

To realize the potential for Zero Energy buildings some challenges related to investment cost, simulation accuracy, construction quality and user behavior needs to be overcome.

2.5.1. The investment cost needs to be reduced

The first challenge is that ZEB buildings tend to be more expensive than traditional buildings. For example, the construction costs of 12 studied low-energy office buildings were budgeted around 40% higher than a standard Spanish office building. Additionally, actual construction costs were generally 25% higher than budgeted [19]. Often, consumers are shown to devalue the operating costs in relation to initial investment costs.

2.5.2. Energy consumption in real operation needs to be reduced

Another barrier for people to invest in ZEBs is the operational performance. Many NZEBs have an energy consumption that exceeds the energy generation [19]. Seven reasons are [29,45]: 1)Passive strategies are often either overlooked or overestimated; 2) The predicted energy generation by solar PV is not achieved due to a significant reduction in efficiency caused by hazy weather; 3) Most contractors do not comply with “best practices” and technical construction accuracy; 4) The installed equipment and usage are not as planned; 5) Incorrect selection of pumps and control system; 6) Less efficient components in active systems; 7) Lower air tightness due to the use of sliding windows or sliding doors.

These problems show a lack of experience, common understanding and communication between the planners and those who carry out the constructions. The lack of accuracy can also be seen through the repeated problem of simplified simulations and use of standard values that does not reflect the real situation, as pointed out by Zhou, et al. [46] and Ascione, et al. [47]. Ascione, et al. [47] analyzed data from the monitoring of a nZEB office building in Berlin. The differences between the simulated and the measured energy need was + 172% for heating and domestic hot water, − 36% for ventilation, − 33% for lighting, − 14% for equipment, − 13% for auxiliaries and + 32% for the PV-system generation. The large deviation between reality and simulation of heating and cooling is critical, especially since about 70% of the energy used in buildings is for heating and cooling normally [48].

2.5.3. Users lack training and motivation for energy efficient behavior

In the resent years, user behavior has been pointed out as an important reason why the real energy need for nZEB buildings are often underestimated [5]. Incautious behavior can increase the energy need by one-third [20]. It is common to believe that users of ZEB can waste energy, because the energy comes from renewable sources [5]. To increase user awareness and make energy efficiency more understood, an energy management system with user friendly interface should be available through cellphones and/or computer [33]. Goal setting, reward systems and tips can be part of this interface [49].

2.5.4. Discussion of the challenges in the ZEB development

The challenge related to lowering the investment cost and improving quality in construction can potentially be solved through industrial construction, as presented later in this article. This is also one of the research topics in CERC that is led by researchers from Lawrence Berkeley National Laboratory (LBNL). LBNL is well known for having developed EnergyPlus and are now developing an open source framework and software, which will allow for occupancy responsive model predictive controls (MPC) for different indoor spaces. This can improve automatic control in the building energy management system, which is important to overcome the mentioned problems related to operational management.

Production of standard units can also improve simulation if operation data can be collected from these buildings' energy management systems to fuel future simulation. For a standardized building it is possible to invest more in making user instructions, because the cost is divided by the number of buildings made. It is also easier to optimize a standardized building over time, for instance by solving problems related to components, maintenance or air leakages [45].

3. Residential ZEBs

The design of a ZEB involves an integrative approach, which simplified can be described by Fig. 2 [29,50].

In the following sections, we will describe the elements in Fig. 2, except for lighting and energy management where the reader is referred to other literature. The presented technologies available for residential ZEBs have mainly been limited to those who are suitable for transportable modules, but Cao, et al. [51] presents an extended table with

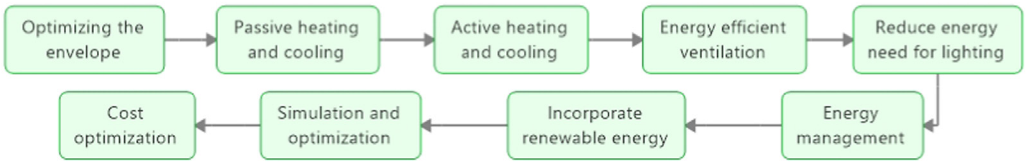

Fig. 2. Steps in planning of a Zero Energy Building [29,50].

references. For additional guidance for a novice in this field, see [52].

3.1. Optimization of the envelope

3.1.1. Shape and orientation

Compact building volumes are optimal in order to reduce heat loss and material use. A container, which is chosen as the modular later in this article, has a large surface area in comparison to floor area. By insulating the building well, the negative consequences of a large surface area are reduced. In addition, a large roof area is desirable for PV generation and the extra material usage is necessary for structural strength. Overheating during the summer may however be a challenge. The external surface can be made white in hot climates to increase reflection and decrease heat absorption. Large external surface area to volume of enclosed space also expand the area where passive design strategies can be used. Another benefit for the container is that narrow buildings can utilize more daylight, as the daylight can only reach so far into a room [29].

Orientation is linked to the wind and sun. For most buildings, a long form stretched along the east-west axis, with maximized south and north facades, is best practice for solar control. As a rule of thumb, the orientation can vary as much as 15 °C and still give acceptable solar control. The north façade receives minimal direct sunlight and usually does not require direct solar control [49]. Rooms with higher internal gains can be placed on the north side of the building, where passive cooling is easier.

3.1.2. Insulation

Insulation is usually more cost-effective in buildings in colder climates [13]. It is less profitable in buildings with large internal heat loads. Insulation in a building with a dominating cooling load can reduce the heat loss during cooling.

Two currently promising insulation materials are VIP and aerogels, which have considerably lower thermal conductivity values than the traditional ones, but their high price limits their current use [53].

VIP has thermal conductivities ranging from between 0.003 and 0.004 W/(m K) in new conditions to around 0.008 W/(m·K) after 25 years, due to diffusion of water vapor and air through the VIP envelope. This is 5–10 times lower than traditional thermal insulation materials, such as mineral wool [53]. Puncturing the VIP envelope, however, causes an increase in the thermal conductivity to about 0.02 W/(mK).

Commercially available aerogels have thermal conductivities between 13 and 14 mW/(m K) [53].

3.1.3. Windows

There is evidence that both health and productivity benefit from the use of daylight in buildings. Looking at objects that are far away allows the eye muscles to rest and helps adjust the internal clock [54]. Daylight penetration is typically limited to two times the floor-to-ceiling height [55].

The North (for the northern hemisphere) provides a diffuse, high quality light. For a side-lighting at the south side, it is recommended to divide the windows into view-windows with solar shading and daylight-windows that always reflects the daylight towards the ceiling. Daylight-windows need to be located high on the wall to direct light towards the ceiling and prevent glare. Since winter heat is desirable, it is better to use south facing glazing with a high Solar Heat Gain Coefficient (SHGC) [54].

The facades facing east, west and south should have dynamic solar shading. A Venetian blind with daylight guiding lamellas installed in the upper part and a standard Venetian blind in the lower part of the window increase daylight penetration deep into the room while blocking direct radiation [56].

External shade elements avoid increased heat gain in summer, thus obviating the need for cooling. In the south, the roof can be projected to protect the large windows from the high summer sun [33].

3.1.3.1. Electrochromic windows and PV glazing. Electrochromic windows are currently the only available technology on the market allowing for the transmittance through windows to be dynamically controlled [57]. Electrochromic glazing is important to achieve as high a visible transmittance as possible in their transparent state in order to obtain a maximum of natural daylighting. For energy regulation, and to be able to shut off as much solar radiation as possible in the cooling season, it is important to have the lowest feasible visible transmittance in the colored state. [58]. Electrochromic glazing has a transmittance of about 0.52, while a standard 3-layer low-energy glass has a transmittance of about 0.7. Therefore, the total area of electrochromic glass must be relatively larger (by about 35%) to keep daylighting at a similar level. Currently, there are cost, warranty, switching time, glare and color rendering issues thwarting the marketability of this glazing technology [59].

PV glazing is an innovative technology which, apart from electricity production, can reduce energy consumption in terms of cooling, heating and artificial lighting. Semitransparent or translucent photovoltaic technology purposely reduces light transmission [60].

3.2. Passive heating and cooling techniques

Cooling represent 9% of the world's electricity demand. In developing countries, cooling is the largest growth area in buildings expected between 2017 and 2040. Passive heating and cooling methods are important to reduce the investment costs for the energy system and the limited space for on-site energy generation. Research into passive design is catalyzed by programs such as Horizon 2020, an initiative from the European Commission [19]. Fig. 3 shows different passive strategies for ZEB buildings.

To save energy for heating and cooling, night-setback, opening of windows and night cooling can be solutions.

Automatic window opening cools the rooms through natural ventilation. One study proposed a small window (0.9 m^2) with a special PI-controller installed at the middle of each floor of a two-story dwelling. The two small windows open proportionally when the outdoor air temperature is less than the indoor air temperature and the latter is higher than 24 °C. The controller tries to emulate human behavior by opening the window to improve the thermal comfort by increasing the ventilation in summer [61].

A smart Energy Management System that takes the weather forecast into account, can take precaution and avoid applying night setback during especially cold days. For a Zero Energy Building, the control system should increase the heating and cooling load if there is excess electricity available and lower the set point to utilize the heat stored in PCMs and thermal mass during periods with electricity shortage.

Smart control is expected to reduce space heating demand by 15% in the EU by 2040, the main saving coming from space heating (65%).

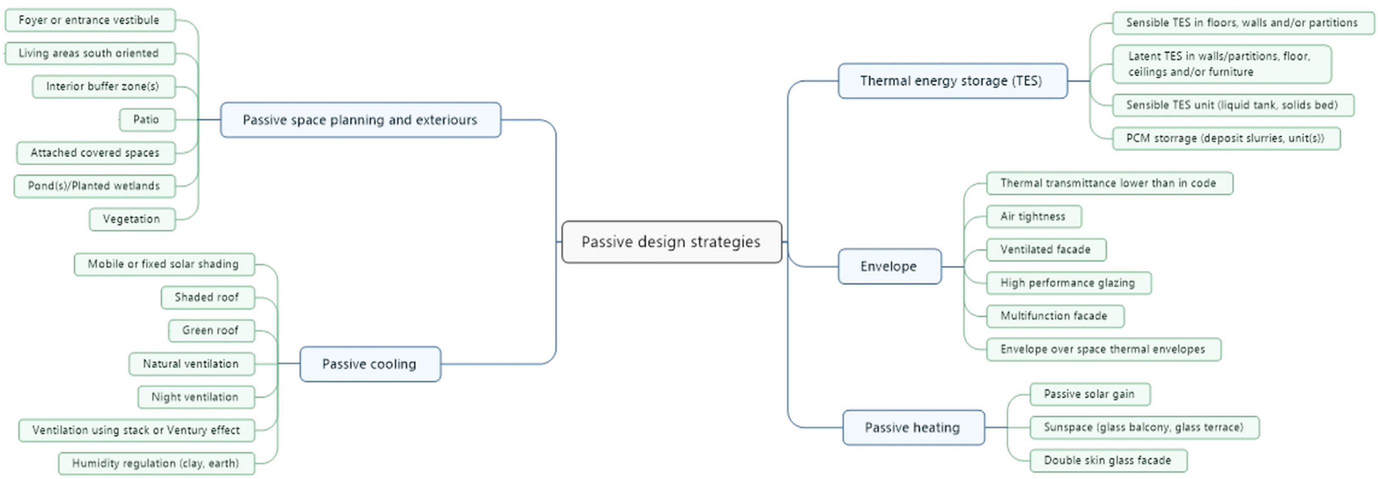

Fig. 3. Passive design strategies. Figure based on table from Rodriguez-Ubinas et al. [44].

3.3. Active heating and cooling

Space heating is responsible for 70%, 62% and 43% of the energy demand in Europe, Australia and the U.S respectively [5]. Heat pumps are the most common active heating system is ZEBs and are therefore chosen as the active heating system to be discussed in this section. One of the reasons for the increase in electricity demand for buildings is that heat pumps make electric space heating more cost-competitive [1]. But as Martinopoulos, et al. [62] presents, there are large variations in the prices of energy carriers, so local energy prices need to be taken into consideration. Since NZEBs want to achieve zero net primary energy consumption over the balancing period, excess generation of renewable electricity must cover any use of fossil fuels. For transportable, solar powered ZEBs, heat pumps stand out as the most viable option. In humid regions as Shanghai, an air-to-air heat pump can also provide dehumidification [63]. A low temperature heating system is preferred, since it will increase the Coefficient of Performance (COP). Due to the cost and limited run periods, micro CHPs require access to cheap biofuels and will mostly be suitable in cold climates without cooling demand.

Heat pumps are characterized by relatively high investment costs per kW, but have a low operation cost per kWh of delivered heat. Consequently, heat pumps are often calculated to cover 40–70% of the heat load, but 60–95% of the energy needs for heating [64]. For a Zero Energy Building, it would be helpful to accept a lower heating set point during the coldest times of the year in order to reduce the investment costs of the heat pump and reduce the energy need of an electric peak load boiler. Alternatively, the heat pump must be dimensioned to cover the peak load, which will only occur a few days in the year, but would result in a lower efficiency factor at part load during the rest of the year. If the cooling demand is high, peak load cooling through a PCM storage tank can be applied.

3.4. Energy-efficient ventilation

Natural ventilation depends on natural driving forces like wind pressure or buoyancy. In naturally ventilated buildings, indoor temperatures more closely match the diurnal and seasonal variations of outdoor temperatures. People recognize this and vary their expectations accordingly [65].

Natural ventilation is an energy efficient way to improve indoor thermal environments when the outdoor temperature is comfortable. Within the temperature range of $-10\,^{\circ}C$ to $+25\,^{\circ}C$, there is a direct linear correlation between the frequency of window use and the outdoor temperature [66]. Occupants in rooms without air-conditioning open windows to improve indoor air quality or allow a cooling effect [67]. For the rest of the year, mechanical displacement ventilation with heat recovery can be used to ensure thermal comfort. Displacement ventilation gives lower pressure loss and consequently lower specific fan power, but mixing ventilation increases the convective cooling.

If hybrid ventilation is chosen, it may be difficult to use a conventional heat exchanger. Then, the exhaust air may be used as a heat source for the heat pump to recover energy through an exhaust air heat pump (EAHP) [32]. Another option is to make use of access heat from PV panels for space heating or pre-heating of ventilated air [68].

3.5. Renewable energy supply

Global energy demand grew by 2.2% in 2017, mostly due to economic growth [4]. Almost all that growth in global power generation in 2017 came from the developing world [4]. Around 14% of the world's population live without electricity, mostly in rural areas in Africa and in the developing countries in Asia [28]. More than 2 billion still use solid fuels for cooking, which is a challenge for air pollution, deforestation and emissions [1]. The options for on-site generation are usually PV, wind power and/or a CHP system. PV and wind power can also contribute to reduce the problem of the millions of premature deaths due to air pollution each year [1]. Until 2040, PV and wind are expected to receive 75% of the new support for renewable electricity generation [1]. PV, solar thermal and heat pump are almost always included in Net Zero Energy Buildings, while CHP and biomass are included in a few larger buildings [33]. For a portable off-grid ZEB, the use of fuel cell might be a future solution. However, an electric battery integrated to solar PV would be a more feasible current solution.

3.5.1. Wind power

The wind speed at the sites is often too low. Efficient building-mount wind power utilization is limited to a few unique cases, due to the minimum wind speeds required (at least 4 m/s annual average), and the unavoidable noise associated with wind turbines [33]. Wind power is better for a group of buildings that can be connected to a nearby wind-farm. A larger wind farm will reduce the maintenance and installation costs, especially in a remote area.

Building integrated wind turbines also causes issues of local turbulence, safety and vibrations. These challenges have to be solved in a convincing way before this technology can be a real alternative or complement to PV [32].

A benefit of wind power is that solar and wind availability tend to have complementary characteristics (i.e. when solar availability is low, wind availability tends to be high, and vice versa), which suggests that solar energy and wind power can, to a certain degree, compensate each other over the course of the year.

3.5.2. CHP

When buildings aren't heated in summer and heat generation is only required for hot water, CHP systems will have short run times. Thus, a low degree of electricity is generated. This changes only in the case of systems that make use of the summer's wasted heat to run a cooling system.

For the time being, the micro fuel cells CHPs are a rather costly technology, and have a relatively short lifetime of 10 years when compared to other technologies, e.g. PV [69].

3.5.3. PV

Solar PV contributed to almost 55% of the new renewable power capacity in 2017. Globally, more capacity from solar PV was added than from any other type of power generating technology [28]; PV added more net capacity than nuclear power, coal and natural gas combined, and twice as much as wind power [28]. New solar PV is now outcompeting new coal in most places [1]. The installed capacity of PV is expected to overtake wind power before 2025, hydropower before 2030 and coal before 2040. PV generation has increased by 10 times, from 0.2% in 2000 to 2% today. In 2040, the global generation is likely to reach 10%, due to falling costs and political support. Investments in solar PV for buildings is expected to play a strong supportive role, although the majority is in utility scale. The levelized cost of electricity (LCOE), which is a metric looking at the average cost of electricity over the lifetime of a project, for PV, has decreased by 65% over the last five years. PV's LCOE are lowest in China and India due to low capital cost and good solar resources. The average global solar PV prices went down to 0.39 USD per watt in 2017, an estimated -6%. The price drop was due to tough competition and easier access to capital caused by a declining risk perception [28].

PV benefits from the fact that the cost difference between small and large-scale installations is not so significant. PV can contribute to the building's prestige and value, and is sometimes even seen as an architectural quality [69]. In addition, there is often a good compatibility between PV generation and cooling demand. PV systems with battery storage can easily be expanded and require minimal maintenance. Among renewable sources, solar PV has the greatest potential to provide for a sustainable future [70].

The estimated service lifetime for a solar PV panels is of 30 years and is based on guidelines from the IEA for the LCA of PV panels [32]. Most PV systems have a warranty of 20–25 years [49].

By replacing roofing or wall cladding with PV panels, the net cost of PV is lowered. This is called Building Integrated Photovoltaics (BIPV) [71]. When compared to glass, steel or other more conventional cladding materials, installing BIPV adds only a marginal extra cost (2–5%) to the overall construction costs [71].

By the end of 2017, Asia was the continent with the most off-grid solar installations. Africa was second with around 60 million people using off-grid solar energy [28]. Off-grid solar systems, often financed through the "Pay As You Go" (PAYG) business model, provided to electricity to more than 360 million people worldwide in 2017 [28]. About 80% of off-grid solar PV sales were PAYG in 2015–2017. Investment in PAYG companies increased by 1400% over the period of 2013–2017 [28]. In countries such as Kenya and Uganda, the number of off-grid systems exceeded the new grid connections in rural areas [28]. In Ethiopia, The National Electrification Program, aims to reach 35% of the population through off-grid systems.

China added more solar PV capacity in 2017 than the world installed in 2015, with a 300% increase in rooftop systems. One of the reasons for this increase is that the government supports rooftop systems for self-consumption to improve electricity access and save investments on the grid [28].

In India, 148 million households use off-grid solar systems, which is 19% of the potential market. Rooftop solar is the fastest growing sector. If the customer can afford the initial investment, they then benefit from lower electricity prices [28]. India's energy demand is projected to more than double by 2040, which means that the rooftop PV capacity will increase and the price for PV will decrease according to the learning curve [1].

One of the developed countries who had a record increase of new PV installations in 2017, mainly in residential buildings, was Australia, where PV with energy storage has become cheaper than electricity from the grid in several regions. 20,800 battery energy storage systems were also installed, 300% more than in 2016.

In Japan, where the public is reticent to nuclear power since the 2012 disaster, the capacity of community solar PV projects increased by almost 50% in 2017 [28]. Due to the new Zero-nuclear policy, the number of PV installations can be expected to continue to grow [72]. In Japan, an estimated 25,000 battery solar systems with battery storage were installed [28].

In Seoul all new apartments must install solar PV, while existing buildings get support to cover 75% of the installation fee. California also requires rooftop PV on almost all new single-family houses starting 2020 [73]. At last, it is worth mentioning that Hungary offers interest-free loans to homes that install solar PV.

3.5.4. Solar thermal

Solar thermal systems have the highest total installed capacity among the renewable energy technologies [74]. 89% of the solar collectors are used to heat tap water, with an average annual system efficiency between 30% and 40% and a market share of 1.5% in European homes [1]. In residential ZEBs, domestic hot water (DHW) is dominant over space heating and can represent 50–80% of the annual heating needs [56]. Flat-plate collectors have low working temperatures (30–80 °C), but are cost-effective and have a long lifetime [75]. For colder climates or higher output temperatures, the Evacuated-tube collector (ETC) can be used (50–200 °C) [75]. Transpired solar collectors are a cost-effective technique for passively preheating outside air. This air may be used to preheat the ventilated air or as a heat source for the air-water heat pump [74]. As the heated air in the collector rises, it is common for the air to collect at the top of the building. During cooling periods, the transpired solar collector is vented to the outside from the top.

Absorption cooling could be an option to increase the utilization of the heat from solar collectors during the cooling season. The COP is usually between 0.5 and 0.75 for single-stage units [76], but the operation time may be limited to 8 h a day for a flat collector on a warm summer day when the temperature of the cooling water is above 30 °C [12]. They are noiseless and have a long lifetime, but the size and weight of solar collectors and absorption chillers provide a challenge for compact transportable homes.

3.5.5. Photovoltaic/Thermal (PV/T)

A Photovoltaic/Thermal (PV/T) system reduces the solar cell temperature and takes advantage of the hot water produced by the wasted heat generated [77]. Removing the heat is useful not only to provide hot water, but mainly to keep the cells efficient, as the electrical power output can drop by 0.2–0.5% for every 1 °C rise in the PV module's temperature [78].

PV/T can reach overall efficiencies of 70% or more, with electrical efficiencies of up to 15 –20% and thermal efficiencies above 50%. These systems can be expected to operate stably for more than 20 years. In most cases, commercial PV/T systems simply integrate existing PV modules and solar thermal collectors into a single panel [79].

3.5.6. Renewable energy storage: electric and thermal

For off-grid systems, there are three main ways to balance the electricity system: energy storage, demand-response, or connecting with other off-grid buildings in a micro-grid. For off-grid ZEBs, some type of energy storage is required to maintain the building's operations when the power generation is lower than the load. For NZEBs, energy storage can increase self-consumption and reduce energy costs during

peak hours. Energy storage is a significant cost issue, both in investment and maintenance [49].

Some part of our energy need can only be covered with electricity, like energy for lights and technical equipment. On the other hand, the energy need for cooling and heating, could often be covered fully or partly with stored thermal energy.

Since off-grid homes may typically be located in rural areas, the electric energy storage should be highly safe and reliable, be easily implemented and have a high specific energy density. Based on the review of Chong, et al. [80], batteries are therefore chosen for further evaluation. Lithium-ion batteries can utilize more than 90% of their capacity without increasing aging mechanisms, for instance by using lithium titanite cells. This significantly more than Lead-acid batteries [81]. Li-Ion batteries have several other advantages over lead acid batteries (Table 1) and are therefore preferable, since the price of Li-Ion batteries are expected to drop due to the learning curve effect, while Lead acid batteries is a mature technology with a stable price.

The price for Li-ion batteries has also dropped rapidly over the last years because of the growing electric car market. From 2007 to 2014, the price dropped annually by about 14% [85]. Many batteries could be reused for energy storage in buildings after they don't satisfy the required range for an electric car. Battery and automobile manufacturers like Tesla (USA) and BYD (China) have also increased their investments into the PV market in 2017, which shows that there is optimism for the combination of PV and batteries in this market [28]. The cost of batteries is projected to half to \$100/kWh by 2030 [1]. Li-ion batteries have been the main reason why global battery storage capacity has tripled in less than three years, with 45% of installations being behind the meter. The battery costs are projected to fall rapidly, increasing the global capacity from less than 4 GW today to 220 GW by 2040, with India alone having 60 GW [1]. The projected growth in electric vehicles causes a demand for lithium that is much higher than the current supply. Consequently, a shortage in the early 2020s might increase the price temporarily until the facilities for increased production are installed [1].

Chong et al. described why a Hybrid Energy Storage System (HESS) that combines a battery and a high specific power storage is often a good solution for electrical energy storage [80]. If the Lithium-ion batteries' lifetime is reduced by rapid fluctuations between charge and discharge, or if higher specific power is required over a short time, a supercapacitor can be added.

Thermal storage is mainly used to provide load shedding in ZEBs, contributing to as much as 20–30% electrical peak load reduction [13]. A Danish study showed that the most cost-effective solution to utilize excess electricity was to use the building's thermal mass as heat storage [10]. Among the eighteen houses in the Solar Decathlon Europe 2012 competition in Madrid, 87% of the houses used one or more thermal energy storage system [13]. PCMs are a natural choice for transportable buildings, due to lower weight than water tanks or thermal mass (for instance brick or concrete or heavy furniture). Generally, 1 m^2 of PCM for every 3 m^3 of air is necessary to ensure an effective heat storage system using a PCM [86]. The most common solution for implementing PCMs into buildings so far is by installing PCM enhanced wallboards towards the interior side of the building's envelope [87]. However, the low thermal conductivity and a large volume change of PCMs during phase transition limit their building application [53].

3.6. Building energy modelling, simulation and optimization

TRNSYS [88] is the most used dynamic building simulation software in literature, followed by EnergyPlus [89], DOE-2 [90], IDA ICE [91] and MATLAB [92,93]. HOMER [94] and Genetic algorithm (GA) [95] are the most common optimization methods/software. HOMER optimizes based on lowest net present cost, but cannot address multi-objective problems for minimizing the net present cost. GA is the most popular method for single objective and multi-objective optimizations (MOO) of hybrid energy systems in previous studies, followed by particle swarm optimization (PSO). [13].

Building designers often have to deal with conflicted design criteria such as minimum energy consumption versus maximum thermal comfort or minimum energy consumption versus minimum construction cost. MOO optimization is consequently often more relevant than the single-objective methodology [96].

Examples of optimization parameters can be cost, insulation thickness, window glazing type and cooling and heating set points. Constraints related to, for instance, thermal comfort or investment costs can be set. Regarding thermal comfort optimization, most researchers refer to Fanger's model and the related parameters Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) [97].

3.7. Economic analysis

As told by the general trend, the most expensive NZEB design solution was at least 3 times more expensive than the cheapest design solution. The same 3:1 ratio was generally observed in terms of Life Cycle Cost (LCC). This clearly illustrates the importance of an economic analysis at the early design stage of NZEBs in order to reach the energy goals with economic efficiency [98].

Assessments of the influence of different climates in the economic-efficient design of NZEBs has indicated that the optimal design solutions for mild winter climates can be significantly cheaper than that of cold winter climates, as for the latter more energy efficient solutions are required. Additionally, because of the low solar radiation, more PV area is required for the offset, which tends to be costlier [98].

4. Industrialized construction to improve the quality of ZEBs

Industrialized construction is a solution to the lack of quality control, which have resulted in higher energy consumption for ZEBs than simulated. Building Information Modelling (BIM), design guidelines and criteria for quality control can improve this. In USA prefabricated housing saw an 14% annual growth from 2012 to 2017 [99]. China also desires to increase the use of industrialized building construction. Only 2% of buildings are currently built in factories, while most other production is industrialized. This is partly due to lack of standards and flexibility in the building code [100]. Prefabricated construction has been forecasted to reach 30% of the construction within ten years, due to incentive policies [101]. The One Belt One Road policy and the founding of Asia Investment Bank provides infrastructure and capital to invest in industrial construction, which can lead to reduced prices due to economies of scale.

Industrial construction has many benefits. Airtightness has specifically been pointed out as a problem in ZEBs. The airtightness of a building made in a factory can be higher as machines can achieve a more accurate connection of joints [102]. Other benefits include: shorter construction schedules with less weather-induced delays, better predictability of costs, 5–10% reduction in material waste and a greater possibility for recycling, less noise and dust generation on site, economy of scale in manufacturing of multiple repeated units and the need for less skilled (but more specialized) workers [100,102–104].

The main drawback for industrial construction is the great initial investment of time and money to achieve these benefits. Industrialized construction requires capital, especially for setting up the factory. Detailed initial planning of the standard units is important. Changeability of the structure is difficult and the module dimensions must fit the local transport restrictions [103].

4.1. Performance data of container buildings at the current stage

There are few articles available in the literature about shipping container buildings, but a few studies are presented briefly here. Atmaca [105] presents a container building used for post-disaster

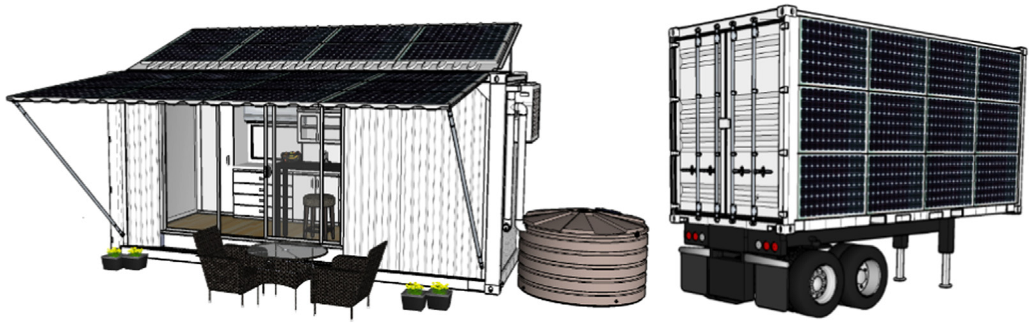

Fig. 4. Individual container home with EAHP and water harvesting system.

housing in Turkey. The container is custom made with a length of 7 m and a width of 2.94 m. The windows have single glazing. The energy need for lighting and equipment are both set to 2 W/m^2 and the container are designed for 4 persons. The walls have 35 mm sandwich plaster board panels, while the roof is insulated with 80 mm glass-wool. The floor is made of 16 mm precast concrete panels. Electric energy need was estimated based on real container home utility bills and questionnaires filled by the users. The total energy need was 106 kWh/m^2, where 75% of the energy need was for heating. Cooling was not installed.

In lack of other studies of container buildings, a prefabricated building module with a similar framework as that of three shipping containers placed side by side is used as a reference [99]. The total floor area is 45 m^2. The building is used as an office space for three people. The walls have a thermal conductivity of 0.3 W/(m^2 K), which is three times as high as the recommendation in the European passive house standard [106], with a thickness of 25 cm. The floor and the roof are constructed in the same way as the walls. The U-value of the windows glass are 1.1 W/(m^2 K), which is around 50% above the recommendations in the passive house standard when the thermal conductivity of the window frame is also included. The building is powered by PV panels on the roof with a total peak power of 5.8 kWp under standard test conditions. The lights are controlled by presence sensors and the ventilation is controlled by window opening. It is cooled and heated by a heat pump with Energy Efficiency Ratio of approximately 3. The building energy need is simulated in Energy Plus and the model is verified to be accurate by measurements, showing a root mean square error of the simulated indoor temperature of 0.25 °C. 71% of the yearly energy demand is from appliances, while the rest is mainly used for heating and cooling (27%). The yearly energy balance shows an excess export of 3477 kWh, so +NZEB is achieved. GHG emissions are about 1.5 t of CO2eq/m^2. The production of materials contributed twice as much as the operational stage. While the life cycle impacts of traditional buildings often are 80% due to the operational stage, the material production stage in this demonstration building contributed to 80%. This shows that more efforts need to be made to save material and energy during production, which can favor industrial construction.

5. Design recommendations for transportable off-grid container buildings

A recent study of a container building for hot and humid climate shows a problem with thermal comfort [107]. Some PV powered container buildings with a pure DC system that have been made by GREE in Zhuhai in China, mainly focused on the electrical part of the design.

For container buildings, some recommended passive strategies are south oriented windows, solar shading in the summer, latent thermal heat storage through PCM, natural ventilation, passive solar heat gain in the winter, airtightness, night-time ventilation (natural or mechanical) and high-performance windows. Narrow buildings utilize more daylight, which is favorable for container buildings. Shading wall overhangs can increase the roof area to maximize the available area for PV. The building can also be placed favorably on the terrain to take advantage of evaporation from rivers, wind or shielding from wind, and shading from trees [49].

Polyurethane foam insulation can be used to level the uneven metal surface of the container wall. Because of the low weight and the high thermal resistance, VIP are ideal to prevent the external metal surface from leading heat in or out of the building. The drawback of those insulation materials is their poor acoustic performance [108]. But this is compensated by the fact that every container unit has its own walls and ceilings, therefore contributing to soundproof a modular building made from several combined container units.

A heat pump can be used for cooling during summer and heating during winter, while natural ventilation (cross-ventilation) may provide cooling in the spring and autumn. PV/T has the potential to reduce the heating demand for hot water, but as long as the hot water consumption is low it may not be worthwhile due to the increased system complexity and the higher investment costs. Hot water can be heated, or at least preheated, passively by a solar collector that circulates water to a storage tank through natural convection [76]. Flat, lightweight models could be suitable for transportable buildings. For a group of container buildings with a shared container dedicated for showering, solar collectors (or a combination of heat pump for hot water heating and PV/T) might be considered.

EnergyPlus is a free simulation software that can estimate the building's energy need and indoor climate. To cost-optimize the energy storage and energy generation, HOMER Pro is recommended.

An example of the design of a transportable container home made from a single shipping container is showed in Fig. 4. Transportable clinics, schools, military camps, showrooms and communication pods are examples of its other usages.

It is also possible to stack containers on top of each other to create modular buildings. The example in Fig. 5 consists of three whole and three half containers. In this case, the staircase is used as a ventilation shaft as well as a solar chimney to reduce the energy need for the exhaust fan in the air handling unit. The fresh supply of air is preheated under the PV surface of the south façade. During the heating season, the air source heat pump is also using preheated air from underneath the PV surface as the heat source, while the outdoor air from the shaded north façade is used to cool the condenser during the cooling season. During the cooling season, the lowest PV-section, covering the front container, is shifted down to shade the solar space and open the top of the solar space for natural ventilation. Green walls on the west and east façade reduce the heat gain from the sun in the morning and evening.

5.1. Standard external container sizes

6.09 m and 12.19 m are the most common container lengths. 6.09 m containers are easier to transport and move, which makes them a better choice for remote locations where the road standards are poor [80]. For container buildings, high cube containers with a height of 2.90 m is the

Fig. 5. Modular off-grid ZEB made from shipping container modules.

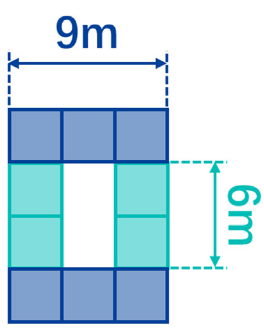

Fig. 6. A courtyard house, inspired by the traditional Chinese Siheyuan.

preferable choice [81]. The standard external width of 2.44 m is very narrow, but experience has shown that it is possible to extend the width up to 3.3 m and still hoist the container on a truck, if the local transport laws allows [109]. If the container home is built with the possibility to insert a side door in mind, the living space can be extended by adding more containers until it culminates into a courtyard house with a garden in the middle (Fig. 6).

5.2. Community of container buildings

For a community of off-grid container buildings (Fig. 7), the buildings can take advantage of shared facilities. The living space in the individual buildings can be increased by moving the batteries to a shared container and connect the buildings in a microgrid. For permanent settlements, a wind turbine could also be connected to the microgrid to increase the reliability of the supply. The toilet and shower facilities can be separated into a shared container with solar collectors on the roof and a large hot water tank to reduce the investment cost and living space in the individual buildings.

6. Perspectives of modular ZEBs

Many, at least in the western world, would question whether containers are suitable for living. The external design of a normal container is not appealing, but there are ways to improve the façade through modular green facades or a simple wooden cladding that also would provide additional shading. It is also important to remember that the targeted market are mainly rural areas, where these buildings can improve the living standard and provide valuable access to electricity, cooling and heating. Although the space of a single container is very limited, it is much better to have a tiny, comfortable home than a large space that cannot be heated, cooled or ventilated at an affordable cost. Simpler, existing, traditional buildings may offer additional space for work and activities, while the container building may be healthier and more comfortable for sedentary activities and sleeping. Containers are already used by many for temporary buildings like working sheds or shelter in refugee camps. There are opportunities to test and expand this business from the existing market.

Fig. 7. Community of container buildings.

It is important that the containers are modular, so additional containers can be connected to expand the building. In this way, container buildings can make it easier to invest in housing since it can be bought piece by piece. Containers already have the lifting points and mechanical strength that are required for transportation. The modifications of the container will however modify the center of gravity and the stiffness, but as long as the construction is solid and rigid, a container is easier to transport than any other building modules.

A disadvantage of steal constructions is that they are obviously more difficult to modify than wooden constructions. This requires that the solutions to connect the containers are prepared in advance, possibly through doorframes that can be joined together. The durability of containers should also be considered. Corrosion may be a problem in humid areas, both due to the outside humidity and humidity generation inside the building if it is not sufficiently ventilated. Still, there is existing experience with surface treatments of containers designed to be transported at the sea. If the surfaces are properly maintained, this challenge can be overcome.

Although PV has several benefits, some drawbacks should also be considered. There is a degradation rate of around 0.5%/year and the shading of a module can dramatically reduce the output from the whole array [28,70,110]. Cleaning of the panels and avoiding trees that create shading could improve the performance, and this must be communicated to the customers. PV systems are more expensive and less efficient than thermal collectors, but, combined with heat pumps, the system efficiency becomes much better. The high initial costs are the main barrier for installation of these systems in constructions [12–14].

GHG emissions for wind power and hydropower were evaluated between 6.2 and 46.0 g CO_2-eq/kWh and 2.2–74.8 g CO_2-eq/kWh, respectively. Even though solar PV has larger impact values (12.1 – 569.0 for multi-Si) due to module manufacturing processes, it still results in lessened environmental impacts compared to hard coal plants that have an emission range of 750–1050 g CO2-eq/kWh [111]. The great variation in emissions for PV panels means that the production methods, the utilization rate, and the energy source of the factory is of particular importance.

6.1. Suggestions for improvement

One of ZEB's greatest challenges seems to be achieving low energy needs in real operation. ZEBs are at an initial state where both the designers, contractors and users lack sufficient knowledge to fully realize their potential. The following sub-sections will suggest strategies that can be applied at each level.

6.1.1. Off-grid ZEBs can simplify how ZEB is communicated

The fact that the users may be unmotivated to save energy and/or lack basic knowledge about the purpose and functionality of different energy saving features in the building seems to be currently overlooked. If ZEB is to be more than a documented label, energy needs in real operation, particularly plug loads, must be considered. The technical solutions should be robust and easy enough to be operated by ordinary people, especially for off-grid solutions in rural areas.

There is a need for clear standards to measure performance against, so the quality of ZEBs can be verified in a way that is easily communicated to the public. The US Department of Energy changed the term NZEB to ZEB since it was hard for the public to understand the meaning of "Net". The cost NZEB definition is favorable in order to offset the difference between the simulated energy need and the real energy need, as most people are interested in saving money. This definition is also easier for the customers to understand, compared to the other more technical definitions.

Tax benefits from the government can give people economic incentives to invest in ZEB buildings. If this financial support is easy enough to claim it can be a good way for the government to promote long term investments in ZEB buildings and their related technologies, which in turn will lower the investment cost for such products. However, for such support to be given, the chosen ZEB definition needs to be clearly agreed upon.

The experience from Denmark shows that users who invest in renewable generation gain an interest in learning about it. Since user behavior has appeared to be one of the major hindrances in realizing net zero energy needs during operation, it is important to make energy monitoring systems with tips, learning videos and easily accessible information. If students could learn this at school, they could also teach their parents; children often learn to use new technology faster than their parents. If the students could be agents for energy saving in their homes, through participating in some sort of competition where they are monitoring their energy consumption at home, they can develop livelong habits of energy efficient behavior.

6.1.2. Use wood instead of steel

An analysis of the life cycle of primary energy consumption and the CO_2 emissions of a container building in Turkey showed that the operation accounted for 90.3% of primary energy use. Consequently, the energy intensive steel production does not seem to have a large impact on the total energy need over the life time of the building. However, the building was heated by a coal burner, resulting in high primary energy use in operation [99]. Steel and cement are two of eight source categories that account for 75% of today's energy sector emissions [1]. This means that, unless recycled shipping containers are reused for building purposes instead of being stripped down, it is a question whether cross-laminated timber or other materials with less environmental impact could have replaced the steel structures partly or fully. Steel structures are responsible for the highest CO_2 emissions in the material production stage (about 700 kg CO_2eq/m^2), while timber structures cause the lowest emissions (about 300 kg CO_2eq/m^2) [99]. Timber is stronger than steel structures per unit weight. Many timbers are either naturally durable or can be easily treated to make very durable. Timber used internally also helps maintain a more stable relative humidity [112]. But in order to use timber, lifting points to carry and keep the module balanced must be designed. Another advantage could be to replace some of the steal for the façade with BIPV.

6.2. Future research needs

It is found there is very limited literature on ZEBs made for industrial construction with shipping containers as a framework. Optimization through simulation is needed, followed by real case studies. Dynamic simulation tools should be used, especially to create good estimates for the load curve for off-grid ZEBs. Thereby, the energy supply system can be simulated under more realistic conditions. Electric appliances alone accounts for more than 20% of the world's electricity demand, more than the heating and cooling demands combined. Appliances was the single factor that caused the largest growth in energy use in buildings between 2000 and 2017 [1]. In developed countries it will remain the largest growth area until 2040. Therefore, more focus should be made on accurately simulating off-grid buildings while including appliances.

An LCA and economical calculation based on local conditions should be performed to evaluate whether shipping container homes are clearly more environmentally friendly than traditional buildings.

A demonstration building should be set up to evaluate the indoor climate in the container building. User feedback should be collected and compared with measurements of CO_2 level, humidity and temperature from the energy management system. The energy management system should also log energy consumption for heating, cooling, ventilation, lighting and electrical appliances separately. This would be helpful to improve the sizing of the energy supply system for future buildings, by basing the simulations off real user data.

There is also a need to research how such off-grid buildings can be optimized in a micro-grid. This includes considering introducing

Combined Heat and Power (CHP) or a wind-turbine as additional energy sources for a community. For sub-urban areas, electric cars may also be integrated to the energy system.

7. Conclusion

Buildings will be the largest consumers of electricity approaching 2040, with an expected 60% growth in electricity needs from today. ZEBs are targeted since they are energy efficient and usually supplied by renewable energy sources on site. The need to reduce the cost of ZEB buildings and improve the quality of construction suggests that the production could be standardized and automated at a factory. Economy of scale could also help fulfill the cost-efficiency goals of the European nZEB definition. The conclusions on the potential for factory-made, modular Zero Energy Buildings can be drawn as:

- Off-grid buildings make it easier to communicate what ZEB implies to the public. It makes it clear that net zero energy must be achieved in real operation and include all the energy needs, especially plug-loads.
- PV has low weight and is now cheaper than conventional energy sources for new installations in many areas. Since the developing countries with the largest expected growth in electricity demand often have good solar resources, PV is expected to play a key role in powering transportable buildings.
- To overcome the high investment cost, off-grid ZEBs would benefit from investment support through loans that are paid back over time, learning from the PAYG finance model that has boosted investments in solar PV in Africa.
- The potential benefits of industrial construction include increased airtightness due to more accurate connection of joints, shorter construction schedules and reduction in material waste.
- Recommended strategies for the design of a transportable off-grid container building include solar shading in summer, passive solar heat gain in winter, natural ventilation or mechanical ventilation with heat recovery, polyurethane foam and VIP insulation. PV is recommended for energy generation, unless a large heating demand and available biofuels favors micro CHP. An air-to-air heat pump provides cooling and heating at a high COP with low investment costs. Lithium batteries are recommended for energy storage.
- A reference building with a structure similar to a shipping container managed to achieve +NZEB in Italy. 71% of the yearly energy demand was for appliances, while the material production stage contributed to 80% of the life cycle impacts. There is still need for more experimental data, as the existing case studies of container buildings in the literature are very limited.
- The emissions from building materials are accounting for an increasing share of the total impacts as operational emissions are reduced through increased energy efficiency. Through Building Information Modelling (BIM) and LCA based on output from BIM software, the emissions from the building materials can be well accounted for at a factory.

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Declarations of interest

None.

References

[1] IEA, World energy outlook 2018; 2018.
[2] Nguyen TA, Aiello M. Energy intelligent buildings based on user activity: a survey. Energy Build 2013;56:244–57.
[3] 2016 World energy outlook; 2016. Available: 〈https://www.iea.org/publications/freepublications/publication/WorldEnergyOutlook2016ExecutiveSummaryEnglish.pdf〉.
[4] BP, BP Statistical Review of World Energy. Available: 〈https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf〉; 2018.
[5] D'Agostino D, Mazzarella L. What is a nearly zero energy building? Overview, implementation and comparison of definitions. J Build Eng 2019;21:200–12. [2019/01/01/].
[6] Kurnitski J, et al. How Defin nearly Net zero Energy Build nZEB 2011;48(3):6–12.
[7] D'Agostino D. Assessment of the progress towards the establishment of definitions of nearly zero energy buildings (nZEBs) in European member states. J Build Eng 2015;1:20–32. [2015/03/01/].
[8] D'Agostino D, Mazzarella L. Data on energy consumption and nearly zero energy buildings (NZEBs) in Europe. Data Brief 2018;21:2470–4. [2018/12/01/].
[9] B. P. I. Europe. Principles For Nearly Zero-energy Buildings; 2011.
[10] Jensen SØ. IEA EBC Annex 67 Energy Flexible Buildings. Available: 〈http://www.annex67.org/media/1057/ebc_annex_67_annex_text.pdf〉; 2015.
[11] Vigna I, Pernetti R, Pasut W, Lollini R. New domain for promoting energy efficiency: energy flexible building cluster. Sustain Cities Soc 2018;38:526–33. [2018/04/01/].
[12] Deng S, Wang RZ, Dai YJ. How to evaluate performance of net zero energy building – a literature research [2014/07/15/]. Energy 2014;71:1–16. [2014/07/15/].
[13] Lu Y, Wang S, Shan K. Design optimization and optimal control of grid-connected and standalone nearly/net zero energy buildings. Appl Energy 2015;155:463–77.
[14] Zhang J, Zhou N, Hinge A, Feng W, Zhang S. Governance strategies to achieve zero-energy buildings in China. Build Res Inf 2016;44(5–6):604–18. [2016/08/17].
[15] Sartori I, Napolitano A, Voss K. Net zero energy buildings: a consistent definition framework. Energy Build 2012;48:220–32.
[16] Simonen K. Life cycle assessment. Routledge; 2014.
[17] Kaklauskas A. Analysis of the life cycle of a built environment. Nova Science Publishers Incorporated; 2016.
[18] Sørensen B. Life-cycle analysis of energy systems; 2011.
[19] Wells L, Rismanchi B, Aye L. A review of net zero energy buildings with reflections on the Australian context. Energy Build 2018;158:616–28. [2018/01/01/].
[20] Toleikyte LKAgne, Bointner Raphael, Bean Frances, Cipriano Jordi, Groote MaartenDe, Hermelink Andreas, Klinski Michael, Kretschmer David, Lapilonne Bruno, Pascual Ramón, Rajkiewicz Andrzej, Santos Jose, Schimschar Sven, Sebi Carine, Volt Jonathan. "ZEBRA 2020 - nearly zero-energy building strategy 2020. Available: 〈http://zebra2020.eu/website/wp-content/uploads/2014/08/ZEBRA2020_Strategies-for-nZEB_07_LQ_single-pages-1.pdf〉; 2016.
[21] E. Commission. Buildings; . Available: 〈https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings〉; 2019.
[22] D'Agostino D, Zangheri P, Castellazzi L. Towards Nearly Zero Energy Build Eur: A Focus Retrofit Non-Resid Build 2017;10(1):117.
[23] E. Commission. Energy consumption in the EU increased by 1% in 2017, Eurostat figures confirm.〈https://ec.europa.eu/info/news/energy-consumption-eu-increased-1-2017-eurostat-figures-confirm-2019-feb-07_en〉; 2019.
[24] E. Commission. EU building stock observatory. Available: 〈https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings/eubuildings〉; 2018.
[25] E. Commission. Smart finance for smart buildings: investing in energy efficiency in buildings. Available: 〈https://ec.europa.eu/info/news/smart-finance-smart-buildings-investing-energy-efficiency-buildings-2018-feb-07_en〉; 2018.
[26] Erhorn-Kluttig H. Cost reduction of new nearly zero-energy buildings: which projects are in the pipeline? Available: 〈http://www.buildup.eu/en/node/54833〉; 2019.
[27] Berardi U. Moving to sustainable buildings: paths to adopt green innovations in developed countries. Walter de Gruyter; 2013.
[28] REN21. Renewables 2018 global status report; 2018.
[29] Attia S, et al. Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. Energy Build 2017;155(Suppl C):439–58. [2017/11/15/].
[30] Mohamed A, Hasan A, Sirén K. Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives. Appl Energy 2014;114:385–99. [2014/02/01/].
[31] Martinopoulos G, Tsalikis G. Active solar heating systems for energy efficient buildings in Greece: a technical economic and environmental evaluation. Energy Build 2014;68:130–7.
[32] Houlihan Wiberg A, et al. A net zero emission concept analysis of a single-family house. Energy Build 2014;74:101–10.
[33] Voss K, Musall E. Net zero energy buildings: international projects of carbon neutrality in buildings; 2013.
[34] N. B. Institute. Getting to zero status update and list of zero energy projects; 2018.
[35] BP, "BP Statistical Review of World Energy 2017,". 2017. Available: 〈http://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-full-report.pdf〉.
[36] Ji Y, Zhu F, Li HX, Al-Hussein M. Construction industrialization in china: current profile and the prediction. Appl Sci 2017;7(2):180.
[37] Zuo J, Zhao Z-Y. Green building research–current status and future agenda: a review. Renew Sustain Energy Rev 2// 2014;30:271–81.
[38] Hu S, Liu F, Tang C, Wang X, Zhou H. Assessing Chinese campus building energy performance using fuzzy analytic network approach. J Intell Fuzzy Syst 2015;29(6):2629–38.

[39] IEA. World Energy Outlook. IEA; 2016.
[40] Molinaroli A. China's clean, green buildings of the future. Available: 〈https://www.weforum.org/agenda/2017/06/china-clean-green-buildings-future/〉; 2017.
[41] E. E. C. S. S. Unit. Energy Flexible Buildings - Annex 67 Factsheet. Available: 〈http://www.iea-ebc.org/fileadmin/user_upload/docs/Facts/EBC_Annex_67_Factsheet.pdf〉; 2016.
[42] U. S.-C. C. E. R. Center. Overview. Available: 〈http://www.us-china-cerc.org/building-energy-efficiency/〉; 2018.
[43] U. S. C. C. E. R. Center. Building energy efficiency. Available: 〈http://www.us-china-cerc.org/building-energy-efficiency/〉; 2018.
[44] Rodriguez-Ubinas E, et al. Passive design strategies and performance of Net Energy Plus Houses. Energy Build 2014;83:10–22. [11//].
[45] Rodriguez-Ubinas E, Rodriguez S, Voss K, Todorovic MS. Energy efficiency evaluation of zero energy houses. Energy Build 2014;83:23–35. [11//].
[46] Zhou Z, et al. The operational performance of "net zero energy building": a study in China. Appl Energy 2016;177:716–28. [9/1/].
[47] Ascione F, Bianco N, Böttcher O, Kaltenbrunner R, Vanoli GP. Net zero-energy buildings in Germany: design, model calibration and lessons learned from a case-study in Berlin. Energy Build 2016;133:688–710. [2016/12/01/].
[48] Good C, Kristjansdottír T, Houlihan Wiberg A, Georges L, Hestnes AG. Influence of PV technology and system design on the emission balance of a net zero emission building concept. Sol Energy 2016;130:89–100.
[49] Hootman T. Net zero energy design: a guide for commercial architecture. John Wiley & Sons; 2013.
[50] Attia S, et al. Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. Energy Build 2017;155:439–58. [2017/11/15/].
[51] Cao X, Dai X, Liu J. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. Energy Build 2016;128:198–213. [2016/09/15/].
[52] Ruzhu Wang XZ. Handbook of energy systems in green buildings. Berlin, Heidelberg: Springer; 2018.
[53] Jelle BP. Traditional, state-of-the-art and future thermal building insulation materials and solutions – properties, requirements and possibilities. Energy Build 2011;43(10):2549–63.
[54] Lechner N. Heating, cooling, lighting: sustainable design methods for architects. Wiley; 2015.
[55] Carrilho da Graça G, Linden P. Ten questions about natural ventilation of non-domestic buildings. Build Environ 2016;107:263–73.
[56] Hestnes AGL, Gunnarshaug Anne, Gustavsen, Arild, Matusiak, Barbara Szybinska, Risholt, Birgit Dagrun, Jelle, Bjørn Petter, Mathisen, Hans Martin, Andresen, Inger, Georges, Laurent, Wiik, Marianne Rose Kjendseth, Schlanbusch, Reidun Dahl, Gao, Tao, Hegli, Tine, Berker, Thomas, Kristjansdottir, Torhildur, Novakovic, Vojislav, Eik-Nes, Nancy Lea, Tolstad, Ole, Zero emission buildings. Fagbokforlaget, 2017.
[57] Jelle BP, Kalnæs SE, Gao T. Low-emissivity materials for building applications: a state-of-the-art review and future research perspectives. Energy Build 2015;96:329–56. [6/1/].
[58] Jelle BP, Hynd A, Gustavsen A, Arasteh D, Goudey H, Hart R. Fenestration of today and tomorrow: a state-of-the-art review and future research opportunities. Sol Energy Mater Sol Cells 2012;96:1–28.
[59] Sadineni SB, Madala S, Boehm RF. Passive building energy savings: a review of building envelope components. Renew Sustain Energy Rev 2011;15(8):3617–31.
[60] Skandalos N, Karamanis D. PV glazing technologies. Renew Sustain Energy Rev 2015;49:306–22.
[61] Hamdy M, Hasan A, Siren K. Applying a multi-objective optimization approach for Design of low-emission cost-effective dwellings. Build Environ 2011;46(1):109–23.
[62] Martinopoulos G, Papakostas KT, Papadopoulos AM. A comparative review of heating systems in EU countries, based on efficiency and fuel cost. Renew Sustain Energy Rev 2018;90:687–99.
[63] Deng S, Dalibard A, Martin M, Dai YJ, Eicker U, Wang RZ. Energy supply concepts for zero energy residential buildings in humid and dry climate. Energy Convers Manag 2011;52(6):2455–60. [6//].
[64] Stene J. Lecture slides from TEP4260 at the Norwegian University of Science and Technology; 2016.
[65] Etheridge D. Natural ventilation of buildings: theory, measurement and design. John Wiley & Sons; 2012.
[66] Yu T, Heiselberg P, Lei B, Pomianowski M, Zhang C. A novel system solution for cooling and ventilation in office buildings: a review of applied technologies and a case study. Energy Build 2015;90:142–55.
[67] Nord N, Tereshchenko T, Qvistgaard LH, Tryggestad IS. Influence of occupant behavior and operation on performance of a residential zero emission building in Norway [2017/10/28/]. Energy Build2017. [2017/10/28/].
[68] Cuce PM, Riffat S. A comprehensive review of heat recovery systems for building applications. Renew Sustain Energy Rev 2015;47:665–82.
[69] Marszal AJ, Heiselberg P, Lund Jensen R, Nørgaard J. On-site or off-site renewable energy supply options? Life cycle cost analysis of a net zero energy building in Denmark. Renew Energy 2012;44:154–65.
[70] Groesbeck JG, Pearce JM. Coal with carbon capture and sequestration is not as land use efficient as solar photovoltaic technology for climate neutral electricity production. Sci Rep 2018;8(1):13476. [2018/09/07].
[71] Petter Jelle B, Breivik C, Drolsum Røkenes H. Building integrated photovoltaic products: a state-of-the-art review and future research opportunities. Sol Energy Mater Sol Cells 2012;100:69–96.
[72] Enteria N, et al. Case analysis of utilizing alternative energy sources and technologies for the single family detached house. Sol Energy 2014;105:243–63.
[73] Daniels J. California regulators approve plan to mandate solar panels on new home construction. Available: 〈https://www.cnbc.com/2018/05/09/california-approves-plan-to-mandate-solar-panels-on-new-homes.html〉; 2018.
[74] Martinopoulos G. 3 - Energy efficiency and environmental impact of solar heating and cooling systems. Advances in solar heating and cooling. Woodhead Publishing; 2016. p. 43–59.
[75] Renné DS. 2 - Resource assessment and site selection for solar heating and cooling systems. Advances in solar heating and cooling. Woodhead Publishing; 2016. p. 13–41.
[76] Wang RZ, Xu ZY, Ge TS. 1 - Introduction to solar heating and cooling systems. Advances in solar heating and cooling. Woodhead Publishing; 2016. p. 3–12.
[77] Li DHW, Yang L, Lam JC. Zero energy buildings and sustainable development implications – a review. Energy 2013;54:1–10.
[78] Prado RTA, Sowmy DS. 7 - Innovations in passive solar water heating systems. Advances in solar heating and cooling. Woodhead Publishing; 2016. p. 117–50.
[79] Ramos A, Chatzopoulou MA, Guarracino I, Freeman J, Markides CN, Hybrid photovoltaic-thermal solar systems for combined heating, cooling and power provision in the urban environment. Energy Convers Manag.
[80] Chong LW, Wong YW, Rajkumar RK, Rajkumar RK, Isa D. Hybrid energy storage systems and control strategies for stand-alone renewable energy power systems. Renew Sustain Energy Rev 2016;66:174–89.
[81] Vetter M, Rohr L. 13 - Lithium-ion batteries for storage of renewable energies and electric grid backup A2 - Pistoia, Gianfranco. Lithium-ion batteries. Amsterdam: Elsevier; 2014. p. 293–309.
[82] Energiewende A, et al. Current and future cost of photovoltaics. Berlin: Agora Energiewende; 2015.
[83] 12VMonster. Comparing lithium-ion batteries with deep cycle lead-acid batteries for home energy storage. Available: 〈https://www.12vmonster.com/blogs/product-questions/li-on-vs-lead-acid-deep-cycle〉; 2016.
[84] Podder S, Khan MZR. Comparison of lead acid and Li-ion battery in solar home system of Bangladesh. In: Proceedings of the 5th international conference on informatics, electronics and vision (ICIEV); 2016. p. 434–8.
[85] Nykvist B, Nilsson M. Rapidly falling costs of battery packs for electric vehicles. Nat Clim Change 2015;5(4):329–32.
[86] Finocchiaro L, Georges L, Hestnes AG. 6 - Passive solar space heating. Advances in solar heating and cooling. Woodhead Publishing; 2016. p. 95–116.
[87] Kalnæs SE, Jelle BP. Phase change materials and products for building applications: a state-of-the-art review and future research opportunities. Energy Build 2015;94:150–76.
[88] T. E. S. Specialists. TRNSYS Available: 〈http://www.trnsys.com/〉; 2019.
[89] N.R.E. Laboratory. EnergyPlus. Available: 〈https://energyplus.net/〉; 2019.
[90] Hirsch JJ. Welcome to DOE2.com. Available: 〈http://www.doe2.com/〉; 2016.
[91] E.S. AB. IDA indoor climate and energy Available: 〈https://www.equa.se/en/ida-ice〉; 2018.
[92] De Boeck L, Verbeke S, Audenaert A, De Mesmaeker L. Improving the energy performance of residential buildings: a literature review. Renew Sustain Energy Rev 2015;52:960–75.
[93] MathWorks. MATLAB; 2019. Available: 〈https://www.mathworks.com/products/matlab.html〉; 2019.
[94] H. Energy. HOMER Pro. Available: 〈https://www.homerenergy.com/products/pro/index.html〉; 2019.
[95] McCall J. Genetic algorithms for modelling and optimisation. J Comput Appl Math 2005;184(1):205–22. [2005/12/01/].
[96] Harkouss F, Fardoun F, Biwole PH. Multi-objective optimization methodology for net zero energy buildings. J Build Eng 2018;16:57–71.
[97] ISO 7730:2005(E). Ergonomics of the thermal environment-analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices local thermal comfort criteria; 2005.
[98] Kapsalaki M, Leal V, Santamouris M. A methodology for economic efficient design of net zero energy buildings. Energy Build 2012;55:765–78. [2012/12/01/].
[99] Tumminia G, Guarino F, Longo S, Ferraro M, Cellura M, Antonucci V. Life cycle energy performances and environmental impacts of a prefabricated building module. Renew Sustain Energy Rev 2018;92:272–83. [2018/09/01/].
[100] Zhang J, Long Y, Lv S, Xiang Y. BIM-enabled modular and industrialized construction in China. Procedia Eng 2016;145:1456–61.
[101] Daily C. Government turns to prefab buildings to save resources; 2016.
[102] Lawson RM, Ogden RG, Bergin R. Application of modular construction in high-rise buildings. J Archit Eng 2011;18(2):148–54.
[103] Smith RE. Off-site and modular construction explained. Available: 〈https://www.wbdg.org/resources/site-and-modular-construction-explained〉.
[104] Kamali M, Hewage K. Life cycle performance of modular buildings: a critical review. Renew Sustain Energy Rev 2016;62:1171–83. [9//].
[105] Atmaca N. Life-Cycle Assess Post-Disaster Tempor Hous 2017;45(5):524–38.
[106] Norge S. NS 3700: 2013. Kriter Passiv Og lavenergihus–Boligbygninger 2010.
[107] Elrayies GM. Thermal performance assessment of shipping container architecture in hot and humid climates. Int J Adv Sci Eng Inf Technol 2017;7(4):1114–26.
[108] Schiavoni S, Sambuco S, Rotili A, Dalessandro F, Fantauzzi F. A nZEB housing structure derived from end of life containers: energy, lighting and life cycle assessment. Build Simul 2017;10(2):165–81.
[109] Tsui E. Cheap Hong Kong-designed 'container homes' the way of the future Available: 〈http://www.scmp.com/lifestyle/article/1908665/cheap-hong-kong-designed-container-homes-way-future〉; 2016.
[110] Shukla AK, Sudhakar K, Baredar P. Design, simulation and economic analysis of standalone roof top solar PV system in India. Sol Energy 2016;136:437–49. [2016/10/15/].
[111] Ludin NA, et al. Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: a review. Renew Sustain Energy Rev 2018;96:11–28. [2018/11/01/].
[112] McGar J. Timber vs steel vs concrete structures. Available: 〈https://sourceable.net/timber-vs-steel-vs-concrete-structures/〉; 2015.